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AUTONOMOUS SPACECRAFT CONTROL

WHITE PAPER ON

ADVANCED AVIONICS CONCEPTS : AUTONOMOUS SPACECRAFT CONTROL

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1. INTRODUCTION

A significant increase in space operations activities is expected because of Space Station Freedom (SSF) and long range Lunar base missions and Mars exploration. There could be several precursor missions to support planning and operations in Lunar and Mars orbits. These precursor missions will involve placing necessary communications satellites in orbit around Mars or the Moon and other support systems on the surface for long range manned operations. Many of the systems will undergo initial testing in the Earth orbital environment.

Space operations will also increase as a result of space commercialization (especially the increase in satellite networks). It is anticipated that the level of satellite servicing operations will grow tenfold from the current level within the next 20 years. This growth can be sustained only if the cost effectiveness of space operations is improved. Cost effectiveness in this perspective translates into operational efficiency with proper effectiveness. This paper presents a concept of advanced avionics, autonomous spacecraft control, that will enable the desired growth, as well as maintain the cost effectiveness (operational efficiency) in satellite servicing operations.

Section 2 describes the concept of advanced avionics that allows autonomous spacecraft control with a brief description of each component. Section 3 describes some of the benefits of autonomous operations. Section 4 provides a technology utilization breakdown in terms of applications. Section 5 provides the candidate programs that will benefit from various autonomous control technologies and their development. Section 6 provides the current status of activities and future milestones expected in each area of autonomous spacecraft control. Section 7 discusses the technology needs and current program holes in the autonomy development. The summary is provided in section 8.

2. ADVANCED AVIONICS CONCEPTS

The advanced avionics concept is based on **total** autonomous control of a spacecraft in all applicable flight regimes without any help from external elements. There are two parts to this basic requirement: first, the onboard avionics system must be capable of performing all functions (This is a necessary driving factor), and second, it must perform all functions without any help from external elements (This is a sufficient part.) The first part identifies necessary functions along with required subsystems and components, while the second part increases its reliability, safety and mission readiness.

By advanced avionics we mean a highly integrated system capable of performing autonomous spacecraft control with high reliability and safety. In this perspective, the system is designed to achieve mission goals (without being dependent on other systems) and to accomplish those functions for which external help is unavailable. By design, the system has proper fault diagnosis, isolation, and recovery capability and is able to cope with unanticipated changes in the surrounding environment. With such capabilities, the system performance results

in high operational efficiency, thus reducing the cost of spacecraft operations.

There are four mission flight segments (see figure 1) considered here for applying our concept: 1) ascent, 2) rendezvous, 3) proximity operations, and 4) landing. Some experts consider parking orbit maintenance and interplanetary cruise as other flight segments. However, the activities performed by a spacecraft during these flight regimes is a subset of activities performed during the coasting phase of the rendezvous segment. Thus, the autonomy requirements are derived indirectly, and a spacecraft capable of autonomous rendezvous is also capable of parking orbit maintenance.

A basic requirement, autonomous control, was applied to each of these segments, and a conceptual design of the avionics system was developed. Each flight segment has some unique control requirements. However, the conceptual design accommodated all these well without having a major impact on the overall architecture. The conceptual design of the avionics system has four major components as shown in figure 2. Each component can be further tailored according to specific flight segment requirements and several sub-components can be added for completeness. Each component is briefly described in following paragraphs.

The flight computer is a key component of an overall autonomous spacecraft control system that includes advanced sensors and intelligent controllers. Advanced computer architectures are required to handle very high computational loads, to interface with distributed, multiple sensor systems, and to properly control the effector systems. The architecture must be capable of performing fault detection, isolation and necessary reconfiguration of the internal hardware. The flight computer component may be a network of many separate processors rather than a single processor. Special processors may be needed for specific functions such as machine vision.

The flight software component must be capable of dynamic adjustment according to the flight segment. This component is responsible for planning the mission, detecting hazards and faults during the mission, evaluating their effects

and generating proper responses, and controlling the trajectory and the mission timeline. Typical navigation, guidance and control software modules are integrated parts of this component. The architecture of this component must be compatible with the distributed nature of the computer hardware and robust for upscaling at the higher function level. Such a system is expected to do the original mission planning onboard the spacecraft and thus will be considerably more capable than current onboard systems.

The advanced sensors component is related to new technology development that is targeted to autonomously measure relevant parameters with high accuracy in real time. These include onboard tracking systems to provide relative state measurements to the spacecraft navigation systems. Operations such as rendezvous, stationkeeping, proximity operations, docking, traffic management, and collision avoidance require measurements of position, attitude, and rates relative to a point or feature on a target spacecraft or object. Operations such as spacecraft landing require measurements of position and rates relative to a landing site, and possibly measurements of terrain contour to avoid hazards such as holes, rocks, and steep slopes. The operation of the sensors must be very reliable with long life and low failure rates. Furthermore, sensors must have built-in health monitoring that provides desired inputs to the flight software component. An advanced sensor may use a data fusion concept to derive a meaningful parameter by appropriately combining several measured parameters. The fusion concept can be applied to data from several sensors to evolve an integrated but distributed sensor system. Alternatively, new technologies may enable weight and power savings with a single sensor replacing multiple sensors.

The intelligent effector is the fourth component of our conceptual design. There will be interfaces with the flight software via the flight computer component. Intelligent effectors are envisioned to have fault tolerant designs and built-in performance monitors.

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3. EFFICIENCY VIA AUTONOMOUS OPERATIONS

The autonomous spacecraft control achieved through this type of avionics system will result in several benefits for overall mission operations. The autonomy onboard the spacecraft will increase the effectiveness with which the spacecraft can perform orbital operations, as well as simplify the current operational procedures requiring periodic mission updates and constant communication with the ground. A major part of calculating the communication windows and associated timelines will be reduced along with the associated support systems. Because the system has built-in support elements, there will less interaction with ground support systems. As a result, the ground facilities will be able to handle more spacecraft operations. These factors will reduce the overall cost of the operations. Thus, there will be a significant increase in the operational efficiency, which translates into cost effectiveness or the reduced unit cost of spacecraft operations.

The reliability and mission readiness of a spacecraft will be improved significantly, especially for the mission planning process that is needed for time-limited missions. It will reduce the planning/replanning workload for the crew as well as for the ground operations.

Success probability of a mission is enhanced simply because the onboard systems are capable of surviving failures by adapting to new configurations. Furthermore, the system is capable of handling the unanticipated changes in the operating environment and adjusting its mission plan accordingly.

Some missions can not be performed without some form of autonomy. For example, an unmanned mission to Mars, which involves events such as pinpoint landing, ascent and rendezvous, could not be accomplished without autonomy.

Since the system architecture is adaptable to various flight segments, there is a capability to switch and/or change the components and subsystems as applicable. The system will require strict enforcement of interface standards and thus improve commonality and modularity among the hardware and software components. The manufacturing, integration and launch processing activities will be standardized, resulting in reduced cost of operations.

As a side benefit, the initial implementation of the autonomous system will provide a basis for estimating the incremental cost and the benefit of greater autonomous capability. Currently, there is no basis for estimating these cost factors.

4. TECHNOLOGY UTILIZATION

Infusion of newer and emerging technologies into a spacecraft system is subject to much closer scrutiny today than in earlier times. The right investments made at the right time will be the critical factor in the efficiency, reliability, and flexibility of spacecraft control functions in the future. Justifying this technology is not a simple task. Infusion of technology produces tangible and intangible results. A seemingly intangible result in one area of the spacecraft system can produce a tangible effect in another area. To assess accrued benefits, since the impacts vary at various levels, all levels of the spacecraft system must be evaluated.

4.1 CLASSIFICATION OF TECHNOLOGY UTILIZATION

For purposes of engineering (i.e., performance) evaluation and cost justification, three kinds of technology utilization can be identified:

1) Replacement applications are those which are needed to replace obsolete hardware or perform existing functions more efficiently, effectively or cheaply. Development work performed at a subsystem level or component level will result in this type of applications. For example:

- Laser Ring Gyro Sensor (improved performance)
- Upgraded Flight Computer with higher speed (to replace the current computers which are no longer manufactured and are becoming obsolete)
- Global Positioning System replacement of Tactical Air Navigation System (replacement of old system as well as improvement in performance)

-New algorithm to compute orbit transfer delta-V's that takes care of finite burn effects and reduces number of maneuvers during rendezvous profile

2) **Enhancing**(Complementary) applications not only help to improve the process but offer advantage for additional support functions and capabilities as well. Research work involving new technology at a system or subsystem level usually results in this type of applications. For example:

   -Laser Docking Sensor that provides range and range rate measurements as well as relative attitude measurements required for docking
   -Vision sensors and associated algorithms that process the data at pixel level and generate orientation information in the reference coordinate frame
   -Variable Thrust Engines will provide thrusting capability for a wide range of delta-V's and also handle G-sensitive payloads at the same time

3) **Enabling**(Essential) applications are those which are essential and absolutely required for future missions. Without these research applications, the mission can not succeed e.g., autonomy for Mars operations. An Earth based control center can not actively participate in the mission operations with the required time granularity. As a result of examining functionality from the perspective of new technology, the emphasis for enabling applications is on deriving unique design approaches and operational effectiveness. For example:

   -Laser Docking Sensor for unmanned spacecraft docking
   -Distributed computing and parallel processing
   -Role of artificial intelligence technology in automated FDIR and replanning
   -Cooperating expert systems
   -Position Reference or tracking systems that provide necessary measurements for robotic path planning
   -Algorithms based on new theoretical frameworks (e.g., fuzzy logic theory) that handle imprecise measurements or information
   -Computer vision system for detecting safe planetary landing areas in real time

These three types of applications are also complemented by another dimension which must be considered when analyzing infusion of technology into existing processes. This dimension is the operations level. Technology applications integrated with other existing subsystems in operations provide a major benefit, especially when systems synergism between components can be created.

5. CANDIDATE PROGRAMS

A large part of the cost of introducing new technology and systems is determined by up-front hardware and software expenses, and maintenance expenses incurred during the lifetime of the application. Commonality can reduce program costs significantly, by spreading non-recurring costs across multiple programs, and by economies of scale. Compared to benefits, the cost items are more readily identified. Yet, the task of estimating those costs has never been perfected. The problem becomes even more complex on the benefit side. There are two sides to the problem: the benefits must be 1) identified, and 2) quantified.

Replacement applications, as described in previous section have the most impact at the component and subsystem levels and are most readily analyzed. Savings potentials can be determined and reliability improvements can be identified.

Enhancing applications improve the quality of performance as well as the reliability, just as the replacement applications. These applications will make the mission operations process more efficient by providing new and better capabilities.

Enabling applications involve an assessment of alternatives which currently do not exist and the associated risks. Concerns and issues with these types of technology infusions reside at the major system level. Certain missions cannot be successfully completed without these types of technology, for example, the Mars Rover Sample Return mission (MRSR).

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While a given program may utilize technologies from more than one of the above classifications, it is useful to group existing and contemplated programs into one of the three areas. From a managerial and programmatic perspective, this effort serves to identify a program with the primary technological level driving (or anticipated to be driving) its success. As distinct from a technical analysis and tradeoff perspective, this programmatic viewpoint serves as a guideline to pervade all aspects of a project.

Table I illustrates a possible grouping of selected NASA programs. Several programs are listed under more than one group. The variety among individual programs within a given classification serves to illuminate the point that technology utilization transcends more generally accepted groupings of programs such as manned vs. unmanned or Earth environment vs. planetary. This indicates a need for sensitivity to intra- and inter-organizational arrangements and working relationships.

Table II identifies functions need by various flight programs, so that the programmatic priorities can be attached and inter-organizational arrangements can be assured. For example, applications developed for autonomous proximity and docking operations can be utilized in several programs. Such applications will therefore have the largest pay-off for its investment. In this table, there are two entries in several columns signifying that the applications are in overlapping categories; in the autonomous rendezvous area, the National Space Transportation System (NSTS) program has some replacement and some enhancement type applications.

6. CURRENT RESEARCH WORK AND PLANS

Advanced development of technologies and systems serves to reduce program development risk and provide better performance. Ongoing research work is focused on the needs identified in the previous sections with emphasis on the operations efficiency achieved through autonomy. Research work is being performed at the advanced avionics concept level as well as the subsystem level. In the efficiency area, the approach is to look at the system or subsystem

from the operations view point, considering how to simplify and automate its operations.

6.1 STATUS OF CURRENT RESEARCH WORK:

Development of The Autonomous Operations (AUTOPS) testbed was started in late 1988. Architecture and design at the system level has been finalized, with major components and functions properly detailed (figure 3). The network protocols are being tested with initial interfaces to the data manager and the vehicle segment. Spacecraft system architecture development is continuing with functional details of each part being identified and documented. This architecture will be tested in the AUTOPS testbed when its initial configuration is complete.

Significant progress in the Autonomous Rendezvous and Docking (AR&D) area for the Pathfinder Program has been accomplished. This multicenter project has research work being performed in new sensor development, trajectory control requirements, new guidance and control algorithms and expert system applications. Several facilities with hardware and software mockups are in place at the Johnson Space Center (JSC) and Marshall Space Flight Center (MSFC) to analyze these operations in detail, and achieve significant effectiveness and efficiency in performing these operations.

Investigations in the area of trajectory control during a rendezvous and docking flight segment is continuing with the preliminary systems requirements document completed in October 1989. Mission scenarios for Mars Rover Sample Return and Satellite Servicer Systems were analyzed to derive requirements in the flight software component, as well as in the sensors and propulsion systems.

Guidance Navigation and Control (GN&C) algorithms development and testing is continuing in the areas of rendezvous and proximity operations. On-orbit operations knowledge capture has begun and the process is well underway to incorporate this knowledge into an expert system. Documentation of this knowledge and its implementation techniques is being performed at this time.

Vision algorithms and the associated hardware processing which are needed in order to perform autonomous docking operations have been identified. Control algorithms based on a fuzzy logic approach have been developed for the translational and rotational control of a spacecraft.

Techniques in system integration and testing that achieve efficiency and flexibility are being identified and applied in the areas of software integration. Comprehensive methods in verification and validation of software, including expert systems, is under development.

Although much more technology development is needed, a substantial amount of development work has already been accomplished in the tracking/vision sensors and processors at the JSC. Several techniques for the docking and tracking system have been analyzed, breadboarded, and evaluated in the laboratory. A laser rendezvous and docking tracking system is being developed for the Satellite Servicer System Flight Demonstration. Autonomous rendezvous and docking, and autonomous landing and hazard avoidance sensor studies are in progress as part of the Pathfinder Program. Also in development are a programmable 3D laser range/doppler imager and an associated processor, an optical image correlator, and a programmable image remapper to reduce the sensitivity of image correlation to scaling (target range) and rotation (target attitude).

Autonomous Landing is also a multicenter project with work distributed among Ames Research Center (ARC), Jet Propulsion Laboratory (JPL), and JSC, with JSC as the co-ordinating center in support of NASA Headquarters project management. The project requirement is to develop technology to land a planetary exploration spacecraft: a) close to the area of mission interest that may contain surface hazards such as large rocks and locally steep slopes, b) with a probability of safe landing greater than 0.98, yet without the payload penalty required for robustness against surface hazards, and c) autonomously.

Current activities are focused on the definition of requirements for landing accuracy and safety, a comparison of alternate navigation approaches

for accurate landing, and a feasibility study of onboard hazard detection and avoidance. The requirements definition work this year is being accomplished by participating in the MRSR Phase-A Study.

An initial version of a model for computing the probability of safe landing as a function of lander robustness and hazard frequency has been developed. The addition of a hazard detection and avoidance function on the lander and information about the spatial distribution of landing hazards on planetary surfaces is needed in order to perform a tradeoff study between lander robustness, landing accuracy and on-board hazard detection and avoidance.

Linear Covariance analysis of navigation errors shows that the addition of radio range/integrated-doppler tracking from the descent vehicle of one or more beacons in orbit or on the ground improves the position accuracy to 0.5 - 2.0km. Landmark tracking using optical images, as is done in the cruise missile, should improve this accuracy. This landing accuracy is comparable to that estimated only from guidance errors by MRSR in Pre-Phase A. A complete simulation of the entry and landing GN&C is needed to identify any guidance and control development that is required to make such landing practical.

6.2 KEY EXTERNAL/INTERNAL CONTACTS:

K. Baker/EF5	Autonomous Landing
C. Gott/FM8	Autonomous Rendezvous
R. Kahl/IZ3	MRSR study
S.Lamkin/EH3	Autonomous Rendezvous & Docking Pathfinder Program
J. Lamoreux/EE6	AR&D and Landing Sensors
J. Moore/IA12	Satellite Servicer System
R. Savely/FR5	Artificial Intelligence

6.3 FUTURE MAJOR MILESTONES:

Tentative milestones for future work in the tracking and vision sensor activities are to review and evaluate the three types of technology (FY89-90) described earlier, develop the most critical and beneficial technologies/techniques (FY90-93), demonstrate autonomous rendezvous, docking, and proximity operations on the Satellite Servicer System Flight

Demonstration (FY93-96), and ground-demonstrate autonomous landing and hazard avoidance sensor/processor technologies and techniques (FY94-96).

Facilities that will support autonomous tracking system technology development and its demonstration include the JSC Tracking Test Bed with 6 degree-of-Freedom Precision Positioner, Cybermation robotic platform, Position Reference System, JSC Manipulator Development Facility and Air Bearing Floor Facilities at JSC and MSFC. These facilities are described in section 6.4.

Major milestones for development of an autonomous landing capability for planetary exploration are: 1) complete definition of requirements for precision landing and for on-board hazard detection and select approaches for development (FY90), 2) Verify landing accuracy using high fidelity simulation based on performance of prototype navigation sensors and guidance algorithms (FY94), and 3) 1G flight test to evaluate/demonstrate performance of on-board hazard detection system prototype (FY96).

Autonomous docking with the laser docking system will be studied in detail during FY90. Characteristics of the laser docking system under development in the Engineering Directorate will be modeled in the existing high fidelity six degree-of-freedom GN&C simulator in Mission Support Directorate to assess the integrated performance envelope and its impact on the guidance and control algorithms.

Detail testing of control algorithms based on fuzzy logic principles using 6 DOF simulation is planned for FY90. Development of a new algorithm that will use the vision measurements to track, approach and dock a payload will be initiated during FY90.

6.4 FACILITIES:

There are several facilities that support the detailed understanding of hardware and software at all levels: overall architecture of the advanced avionics, its components as well as subsystem level activities. The following facilities are used for the current research work performed in several areas:

1. Integrated Graphics Operations Assessment Laboratory (IGOAL)
2. Autonomous Operations Testbed (AUTOPS)
3. Tracking Test Bed/ 6-DOF Positioner
4. Hybrid Vision Laboratory
5. Manipulator Development Facility
6. Air Bearing Floor Facilities at JSC and MSFC
7. Contact Dynamics Simulation at MSFC

IGOAL facility

The IGOAL facility, located in Building 12 at JSC, is used for: a) systems engineering and operations analysis that requires man-in-the-loop interaction, and b) development of graphics software tools hosted on state-of-the-art graphics processors for real-time and non real-time operations assessments. It also provides capability to perform visual assessment of space operations and develop proper procedures for handling payloads. The visualization provided by elaborate graphics systems enhance the development of mission timelines with reduced time in moving a payload and yet simultaneously maintain proper clearances among the surrounding objects. The facility can also be used for properly understanding how proximity operations including berthing and deberthing are taking place and how these can be improved.

AUTOPS facility

The AUTOPS facility is designed to fully develop the advanced avionics concept from the systems view point. It is a test bed to check out all parts of the flight software component described earlier. The AUTOPS architecture directly supports distributed processing and allows testing of all types of hardware and software subsystems of a spacecraft. The AUTOPS testbed will be implemented on a network of workstations with proper interfaces to a graphics computer that will provide 3-dimensional visualization of space operations. It will be possible to test the performance of several advanced software technologies such as Expert Systems and their interfaces simultaneously.

For certain mission scenarios, the facility will provide real-time visualization of mission

operations. Real-time performance of the testbed will provide a capability to develop detailed operations procedures and identify important links and backup capabilities required to achieve efficiency. The testbed will be extensively used for: a) deriving performance requirements for intelligent sensors and effectors, b) assessing their impact on a mission timeline and overall operations, and c) assessing the performance of expert systems during mission.

Tracking Test Bed/6-DOF Positioner

The Tracking Test Bed is a 20 ft. wide x 300 ft. long indoor test range in Building 14 at the Johnson Space Center. This facility is used to develop and test various spacecraft onboard tracking systems, including a laser docking sensor and 2-D and 3-D machine vision systems. Within this facility, are a multi-camera based Position Reference System, two Cybermation remotely controlled robotic wheeled platforms, and a Six-Degree-of-Freedom (6-DOF) Positioner.

The Cybermation robots and Position Reference System are used to establish known two-dimensional relative motion between a tracking sensor and a target for coarse performance measurements.

The 6-DOF Positioner provides a means of precisely and dynamically simulating the relative position and orientation of a tracking sensor and a target. This capability will be used to precisely determine the dynamic performance of various tracking/vision systems in measuring range, bearing, attitude and associated rates. This system will be used to verify the performance of precision sensors for autonomous rendezvous and docking. The 6-DOF Positioner (figure 4) consists of three main subsystems: (1) a 12-meter granite rail which supports an air bearing table on which the sensor is mounted, (2) a mobile granite table on which the target is mounted, and (3) a 386/25 MHz controller processor, an IEEE bus controller, and a Global Positioning Satellite timing receiver to provide time tags for the various subsystems. The 6-DOF Positioner will provide angular accuracy of 0.001 degree and linear accuracy of 10 microns.

Hybrid Vision Laboratory

The Hybrid Vision Laboratory is a black-walled facility in Building 14 at the Johnson Space Center which houses an air suspension optics table with an extensive array of optical components and lasers. The laboratory supports development and testing of both digital and analog machine vision systems. These include a real-time optical correlator complete with cameras, monitors, spatial light modulators, and supporting computers and electronics. The laboratory also contains the Programmable Remapper image warping system, which is a video-rate geometric image transformation processor designed by NASA/JSC.

Manipulator Development Facility

This facility is a full scale mock-up of payload bay with one 'G' Remote Manipulator System (RMS) located in building 9A at JSC. There is a Systems Engineering Laboratory (SEL) computer to compensate for one 'G' earth environment effects so that the motion of RMS has a feel for orbital environment. (A real RMS will not work in one 'G' earth environment.) The facility is used for training the crew in the RMS operations with payloads and in developing procedures and timelines.

JSC Precision Air Bearing Facility (PABF)

This facility has been in service since 1976. It provides the capability for reduced friction simulations of zero gravity in support of development of hardware and operational procedures for NASA spaceflight programs.

The air bearing table is 24 feet in length by 21 feet wide. The twenty-one 6 inch thick steel plates that comprise the table are precision ground to a tolerance of 0.0005 inches over any arbitrary 2 foot by 2 foot section. The entire table can be leveled to within 0.011 inch. This degree of precision permits a unit under reduced pressure, thus minimizing the skating effect commonly encountered in similar facilities. The steel construction of the bearing surface endows it with great durability. The surface, as cast, has a Brinnell hardness of 180 to 220, offering a high resistance to scratching and gouging.

The PABF has been employed in Manned Maneuvering Unit (MMU) testing, evaluation, and flight training. Its sensitivity allows the evaluation of dynamic responses to disturbances induced by factors such as crew limb motion and umbilical/tether dynamics.

MSFC Teleoperator and Robotics Air Bearing Floor

The air-bearing floor is a 4200-square-foot precision cast epoxy isolated pad on which full-scale mockups of spacecrafts, structures and modules can be floated on air bearings. A six-DOF mobility unit operates under closed loop remote control to allow accurate, repeatable positioning of high fidelity instrument/video/capture mechanisms (weighing up to 400 pounds) in order to simulate rendezvous and docking maneuvers with full-scale mockups under controlled variable lighting conditions. Full video and telemetry are returned via RF link. A payload mounted on this simulator can represent a moving satellite during docking simulations. Additional air bearing and stationary stands are available for mounting targets on or about the flat floor. Free body dynamic models of motion are run on a VAX computer to control and direct the mobility unit and the dynamic target simulator.

MSFC Contact Dynamics Simulation

The MSFC Contact Dynamics Simulator is a hydraulically driven, computer controlled, six-degree-of-freedom simulator. The facility can handle payloads up to 20,000 pounds and accelerations up to three G's. The dynamics of two bodies are represented in the simulation, and most vehicle motions can be provided, including spinning, coning, and tumbling. The simulation includes the characteristics of the vehicle control system, structural dynamics, and manual control. Some of the safety features provided include pneumatic positioning of test articles to prevent excessive contact forces, breakaway bolts, and software limits on forces and moments. These features protect the test articles during simulations.

7. TECHNOLOGY NEEDS AND HOLES IN THE ACTIVITIES:

The research work and progress in this area of autonomous spacecraft control is not complete nor comprehensive. Certain flight segments have received particular emphasis in anticipation that the results will be applicable across a range of programs. It is also expected that the technology developed in these areas will be useful in the areas where research work is at low level.

Current activities in the Fault Detection, Isolation and Recovery (FDIR) techniques are at a very low level and assume that the system being implemented will be on the ground and not on the spacecraft. It should be emphasized that these FDIR systems will have to be onboard for Lunar and Mars missions, and that they must provide reliable performance. Furthermore these systems must work within the framework of autonomous operations and its architecture.

There is a low level of activity in the autonomous ascent, traffic management and debris avoidance areas. However, these activities are not closely tied in with the activities in AR&D, Autonomous Landing, Vision/tracking systems, and AUTOPS and IGOAL facilities. From the view point of autonomy, there should be more information exchange and cooperative plans.

For a complete development of autonomous spacecraft control, there should be a well designed testbed that allows an evaluation of the software and its integration with the hardware as a total system, and that considers the performance of the system from an operations point of view. An extensive amount of expert knowlege capture needs to occur in the software area in order for autonomous spacecraft control to reach fruition. For each of the four mission segments (ascent, rendezvous, proximity operations, and landing), the onboard software must be able to plan and as well as properly execute trajectory maneuvers. During a mission, circumstances may not allow the engineers on the ground the opportunity to plan each segment and then to provide the spacecraft with the necessary information.

Several facilities with unique hardware and associated software are in place or becoming in

place. There should be a comprehensive plan either to tie all these facilities and activities into one testbed or to implement sufficient overlap for smooth transition from one facility to another. This will enable migration of autonomy onboard the spacecraft at a faster rate.

The distinction between automated and autonomous operations is not clearly understood at management levels, much less the cost and benefits of autonomy. As a result, the development of applications is postponed until it is really required for completing the mission. Applications are then developed with no emphasis on operational efficiency. The end result is very high operational cost or no cost effectiveness. Unless more emphasis is placed on the development of technologies for autonomy, near Earth operations will continue to be inefficient and unmanned remote operations will not be feasible or will meet with decreasing mission success.

Most of the basic technology required for autonomous spacecraft control exists today in unintegrated and small rudimentary applications form. Onboard task planning and management systems, intelligent GN&C systems, advanced sensors, and intelligent effectors are all being worked, albeit at an immature level. What is required, consequently, is a system integration that is targeted towards specific functions and capability. Currently, this integration activity is performed only when it is absolutely needed by a program. There is an understandable reason for this behavior: initial development of applications is driven by budgetary constraints and needs, rather than by completeness of applications. As an example, the vision algorithms have been developed for computing relative attitude angles, but they are not integrated into space operations because no program absolutely requires or has plans to use them.

In the tracking sensor area, one of the most promising, but least mature technologies is robotic vision. Robotic vision has great potential for autonomous operations such as inspection, grappling, docking, berthing, surveillance/traffic management, and landing. Better sensors are needed, including 3D laders, optical image correlators, and digital processing algorithms for 2D and 3D imagery.

8. SUMMARY

Improving the operational efficiency of current programs and satisfying the operational requirements of new programs will require new technologies for autonomous spacecraft control. Additional benefits and efficiencies can be achieved by common usage of spacecraft control hardware and software across multiple programs.

Until there is a high level commitment and associated multiyear funding for autonomous spacecraft control, the activities performed in these areas will not result in a tangible benefit for the space program. Cost effectiveness and operational efficiency for space operations will not be achieved nor the long range Lunar and Mars missions without this autonomy onboard the spacecraft.

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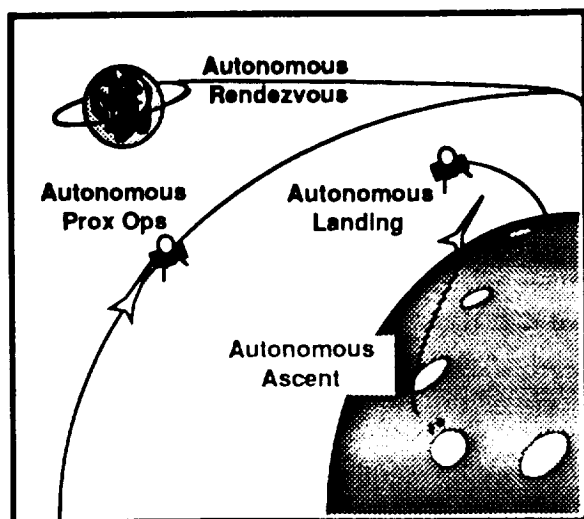
FIG. 1 Flight Segments for Autonomous Spacecraft Control
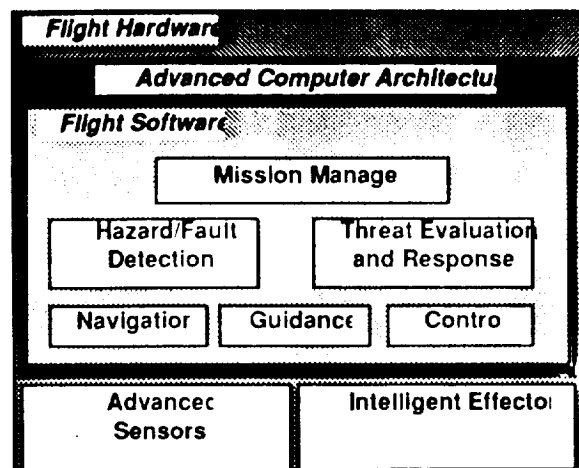
FIG. 2 Components of Advanced Avionics System

TABLE I. CANDIDATE PROGRAMS AND TECHNOLOGY UTILIZATION

REPLACEMENT (Substitutive)	ENHANCING (Complementary)	ENABLING (Essential)
NSTS	NSTS	
SSF	SSF	
	OMV	
	ACRV/CERV	ACRV/CERV
	Satellite Servicer System	Satellite Servicer System
	OTV	
	Advanced Launch System (ALS)	
	AOTV	AOTV
	Manned Lunar	Manned Lunar
		Mars Rover Sample Return
		Manned Mars

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TABLE II. AREAS OF AUTONOMOUS CONTROL VS. PROGRAMS

Candidate Programs

Functions	NSTS	OMV	SSF	ALS	CERV/ACRV
Autonomous proximity operations and docking	Enhancing	Replacing/ Enhancing	Replacing/ Enhancing	————	Enhancing/ Enabling
Autonomous Rendezvous	Enhancing	Replacing/ Enhancing	————	————	
Autonomous Landing	Enhancing	————	————	————	Enhancing/ Enabling
Autonomous Ascent	Replacing/ Enhancing	————	————	Replacing/ Enhancing	————
Traffic Management	————	————	Enhancing	————	————
Debris Avoidance	————	————	Enhancing	————	————

TABLE II. AREAS OF AUTONOMOUS CONTROL VS. PROGRAMS (continued)

Candidate Programs

Functions	SSS	MRSR	Shuttle-C	OTV/AOTV	Lunar Base & Manned Mars
Autonomous proximity operations and docking	Enabling	Enabling Enabling	Enhancing/ Enabling	Enhancing/	Enhancing
Autonomous Rendezvous	Enabling	Enabling Enabling	Enhancing/ Enabling	Enhancing/	Enhancing
Autonomous Landing	————	Enabling	————	————	Enhancing
Autonomous Ascent	————	Enabling Enabling	Enhancing/	————	Enhancing
Traffic Management	————	————	————	————	Enhancing
Debris Avoidance	————	————	————	————	————

Flight Hardware Modeling and Subsystem Integration

Flight Software Modeling

Evaluate:
- System and Environment Models
- Autonomous Operations Cost/Benefits
- Applicability of Artificial Intelligence Technology
- Algorithm Performance
- Sensor Requirements and Capabilities
- Effector Requirements and Capabilities
- Mission Success Probabilities
- CPU Performance Requirements
- System Architecture
  - Distributed Processing
  - Parallel Processing
  - Symbolic Co-processors
  - Fuzzy Logic Co-processors
  - Computer Vision
  - Data Bus Bandwidth Requirements
- Communication Protocols
- Process Synchronization
- Fault Detection
- Fault Tolerance
- Fault Management
- Flight Software/ Hardware Interactions
- Vehicle Communications Requirements

Mission Manager
- Goal Prioritization
- Activity Planning
- Task Distribution
- Activity Monitoring
- Task Coordination
- Conflict Resolution
- Status Monitoring
- Anomaly Detection
- Fault Isolation
- System Reconfiguration
- Information Distribution
- Re-Planning

Navigation
- State Estimation
  - Inertial
  - Relative
- Error Propagation
- Hazard Detection
- Collision Probability Determination
- Optimal Measurement Selection and Scheduling
- GPS Processing
- Filter Development
- Sensor Reconfiguration

Guidance
- Autonomous Rendezvous
- Autonomous Stationkeeping
- Autonomous Docking
- Collision Avoidance
- Low Thrust Guidance
- Ascent Guidance
- Entry Guidance

Control
- Optimal Jet-Select
- Dynamic Plume Impingement Avoidance
- Redundant Manipulator Control Laws
- Force Feedback Control Laws
- Path-planning and Collision Avoidance
- Ascent Flight Control
- Entry Flight Control

Sensors
- Laser Ranger
- GPS Receivers
- LADAR/RADAR
- Rate Gyros
- Imaging Systems
- Transponders
- Accelerometers
- IMU's

Effectors
- Reaction Control System
- Momentum Wheels
- Rocket Engines
- Magnetic Torquers
- Manipulators
- Aero-control surfaces

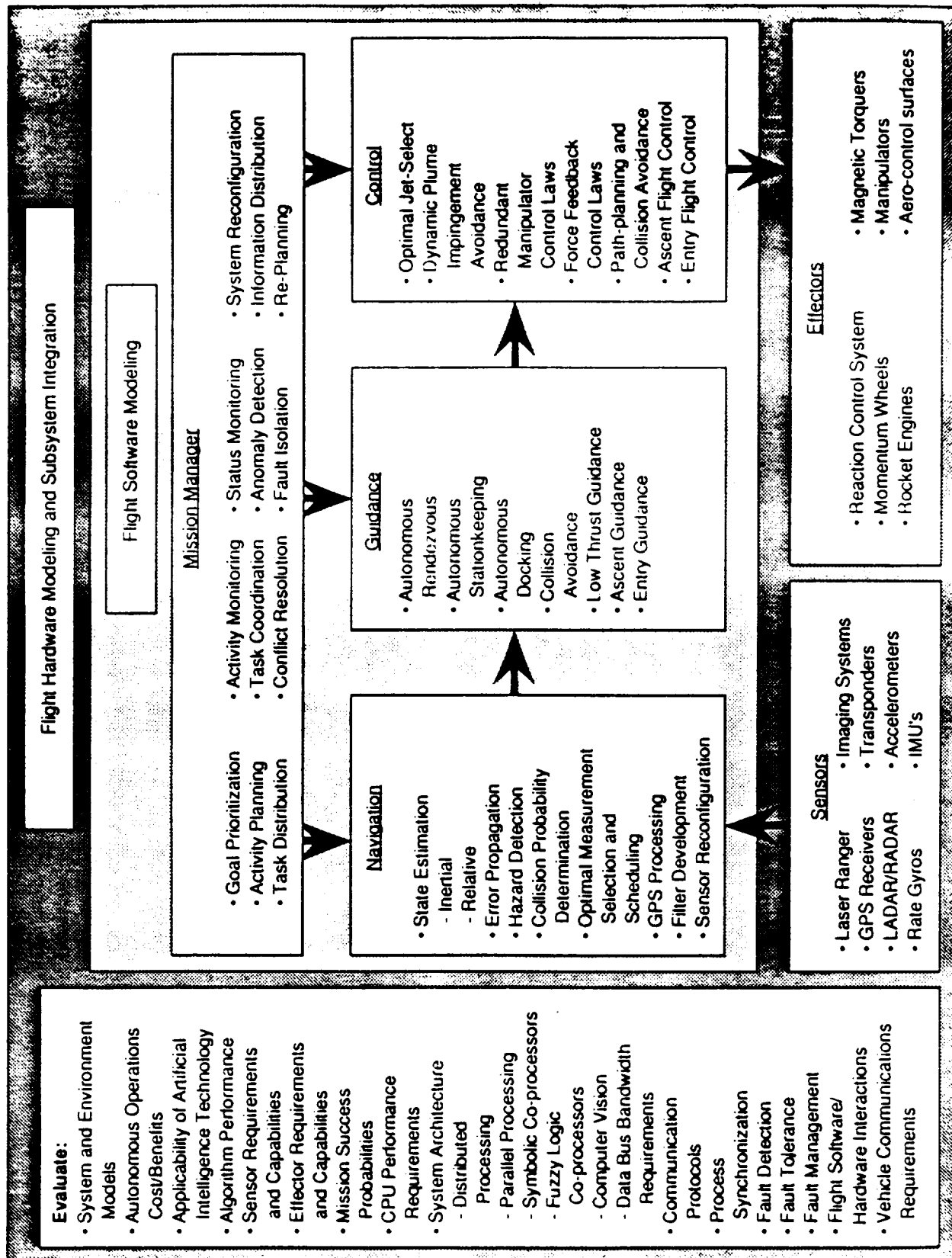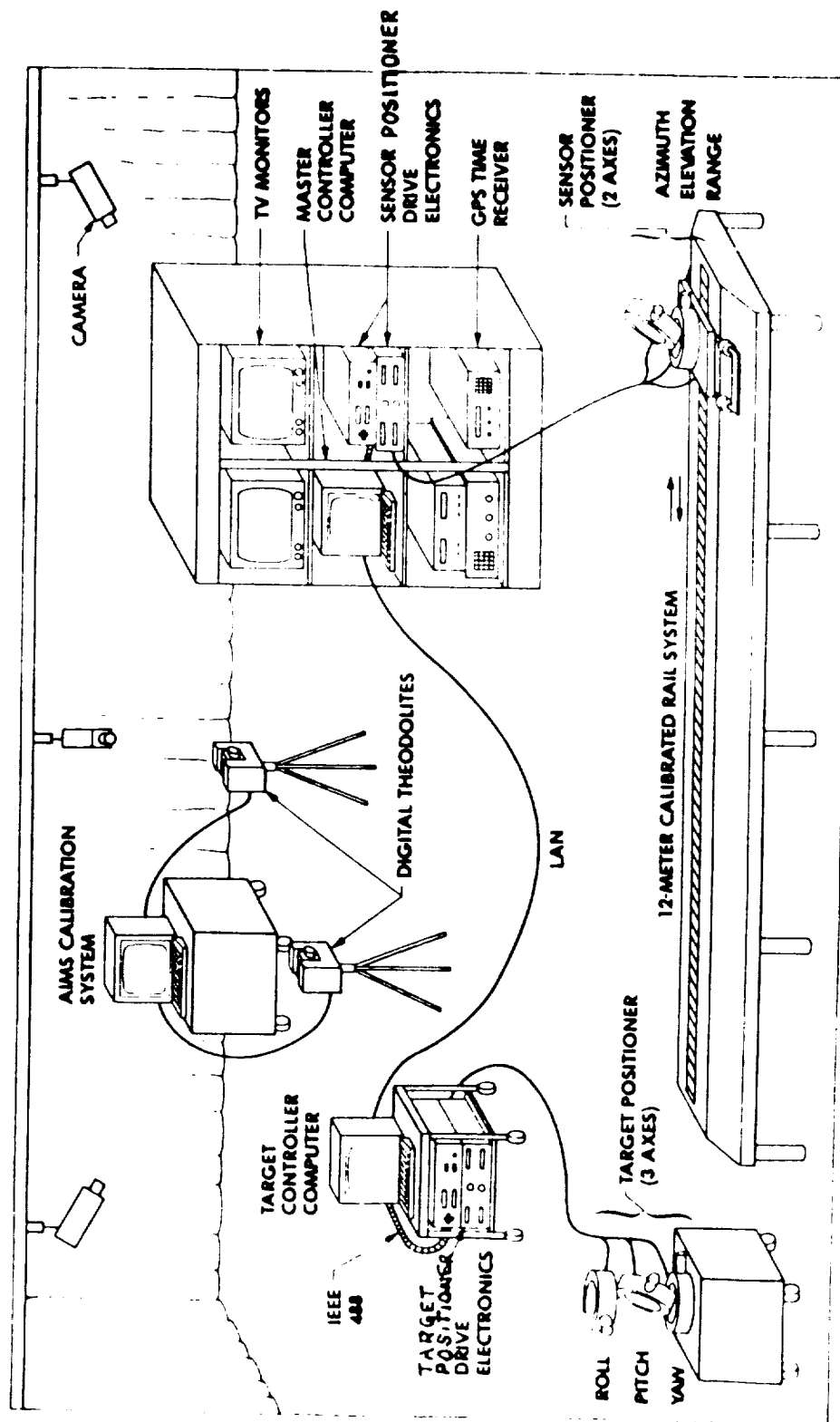Figure 3 DETAIL ARCHITECTURE OF AUTOP'S TESTBED

Figure 4   SIX DEGREE-OF-FREEDOM FACILITY